

USE OF LINEAR PERSPECTIVE SCENE CUES IN A SIMULATED HEIGHT REGULATION TASK

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ABSTRACT

As part of a long-term effort to quantify the effects of visual scene cuing and non-visual motion cuing in flight simulators, the Air Force Aerospace Medical Research Laboratory (AFAMRL) has completed an experimental study of the pilot's use of linear perspective cues in a simulated height-regulation task. Six test subjects performed a fixed-base tracking task with a visual display consisting of a simulated horizon and a perspective view of a straight, infinitely-long roadway of constant width. Experimental parameters were (1) the central angle formed by the roadway perspective (30 or 60 degrees) and (2) the display gain (-0.3 or -0.6 degrees change in central angle per foot change in altitude). The subject controlled only the pitch/height axis; airspeed, bank angle, and lateral track were fixed in the simulation.

The average RMS height error score for the least effective display configuration (60 degree central angle, lower display gain) was about 25% greater than the score for the most effective configuration (30 degree angle, larger gain). Overall, larger and more highly significant effects were observed for the pitch and control scores. Model analysis was performed with the optimal control pilot model to characterize the pilot's use of visual scene cues, with the goal of obtaining a consistent set of independent model parameters to account for display effects.

INTRODUCTION

The Air Force Aerospace Medical Research Laboratory (AFAMRL) is studying visual scene cuing and non-visual motion cuing in operational and simulated aircraft missions. A set of experiments has been designed to provide a data base which will

support development of a cuing model centered on the optimal control model (OCM) of the human operator. This model is intended to permit prediction of cuing effects in experimental situations not tested, and ultimately to aid in the specification of simulation hardware.

The task of low-level flight is the operational mission simulated in the experimental program. (In the military context, low-level flight may involve high-speed flight relatively close to the terrain to avoid detection while over enemy territory.) This task was chosen because of its relevance to Air Force operations, and because it provides a realistic framework for exploring the pilot's use of various visual and non-visual cues.

Research into visual scene cuing is being concentrated on cues provided by lines and texture elements in the visual scene. This paper summarizes the results of an initial experiment involving the use of linear perspective cuing -- specifically, the cues provided by a perspective display of a straight, indefinitely- long roadway. The reader is referred to recent articles documenting modeling efforts related to the pilot's use of texture-related cues [1,2], and to another paper presented at this Conference summarizing a study of g-seat cuing [3], also conducted as part of the AFAMRL research program.

METHOD

Displays

The displays were computer generated scenes consisting of line drawings of a perspective view of a road and a horizon. The central perspective angle of the road changed as a function of altitude, and the vertical position of the horizon line and simulated roadway changed as a function of the pitch state of a simulated aircraft. The left two frames of Figure 1 indicate level flight at low and high altitudes. The right two frames indicate pitch down and pitch up states. When the aircraft was level, the horizon was at eye level. The screen was 38 cm wide and viewed from 38 cm resulting in a horizontal optical size of 53.1 deg. The image of the road was always symmetrical but the horizontal location of the vanishing point was continuously perturbed using a sum-of-three-sines forcing function. This resulted in a quasi-random simulated "crabbing" motion of the aircraft beyond the control of the observer and uncorrelated with the vehicle states. The purpose was to eliminate any spurious cues arising from unintended static reference marks.

The experimental design called for four scene classes formed by crossing two levels of the central angle of the road (30 and 60 deg) and two levels of the display sensitivity or gain (-.3 and -.6 deg/ft). Display gain refers to the change in road angle per unit change in altitude. The relationships between central angle and roadway parameters are:

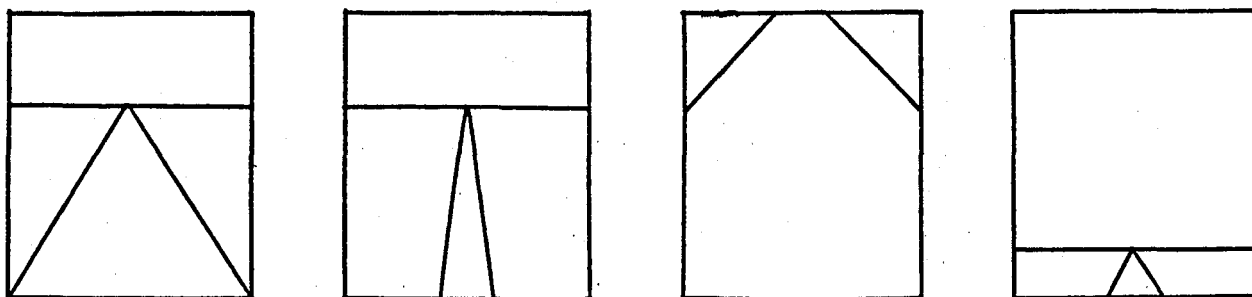


FIG. 1. EXAMPLES OF DISPLAY STATES

$$\beta = 2 \tan^{-1} \frac{W}{2H} \quad (1)$$

$$\frac{\partial \beta}{\partial H} = -\frac{W}{H^2 + \frac{W^2}{4}} \quad (2)$$

where β is perspective central angle in radians, H is height above roadway in feet, and W is the width of the road in feet. Because the central angle decreases with increasing altitude, the display gains are negative as indicated by Equation 2.

The gain and angle requirements uniquely determine the physical roadway width and initial altitude values which in turn are used for computer scene generation. Table 1 presents the values.

NOMINAL CONDITIONS

Height ft	Width ft	Road Angle deg	Display Gain deg/ft
95.5	51.2	30	-.3
47.7	25.0	30	-.6
165.0	191.0	60	-.3
83.0	95.0	60	-.6

Because it is more consistent to model perceptual limitations in terms of perceptual units, rather than simulation units, visual variables (central angle and display gain) were selected as the primary experimental variables, and values for the corresponding physical scene variables (road width and

height) were selected to yield the desired combination of visual values. Treatment of perceptual limitations within the OCM is discussed later in this paper in the presentation of model results.

Control.

The displays changed from their initial conditions as a function of observer pitch control and simulated vertical gust. The actual relationship between these inputs and display effects was determined by a simulation of the flight dynamics of an F-16 aircraft flying at 400 knots at a 100 ft altitude. For details see Levison, Zacharias, and Sinacori [4].

The observer controlled the simulated aircraft by means of a force stick mounted to the side of an aircraft seat. Only pitch commands were registered.

Forcing Functions

The forcing function was formed by summing 13 sinusoids with amplitudes and frequencies to approximate a first-order gust spectrum having a break frequency of 12 rad/sec and an RMS amplitude of 7.7 ft/sec. This gust spectrum is, in turn, an approximation to the Dryden gust spectrum appropriate to a nominal flight condition of 400 kts at 100 feet above sea level -- a gust model that is recommended for aircraft flying qualities studies [5].

Procedure

Six people (three men, three women) participated as test subjects. None were pilots. The observer's task was to keep altitude constant during the course of each simulated flight. An alternate conception of the task is that it involved compensatory tracking of the central roadway angle. This task is interesting in that, once a trial began, no reference angle was presented: An observer tracked his or her concept of what 30 or 60 deg looked like.

Each flight or trial began with 15 sec of viewing the static display corresponding to the initial scene of one of the four conditions. A ready signal was then given and both the gust and force stick were activated. The dynamic phase lasted 120 sec of which only the last 102.4 sec were used as data. At the end of each trial, the observer's mean, standard deviation, and RMS height error were displayed. Four trials, one for each condition, constituted a session and observers ran for two sessions a day.

Conditions were uniquely randomized within each training session, and were further constrained to form a Latin Square over the last four sessions (16 data trials). These sessions, which

began when an observer reached an asymptote based on RMS height error, provided the data for formal analysis. On the average, the subjects received 43 training sessions.

DATA ANALYSIS

Performance Scores

Standard deviation (SD) height error scores were averaged across replications to provide mean performance scores for each subject, each condition. Subject means were then averaged to provide group mean performance and subject-to-subject variability. T-tests were performed on subject-paired SD scores to determine potentially significant differences between all pairs of experimental conditions.

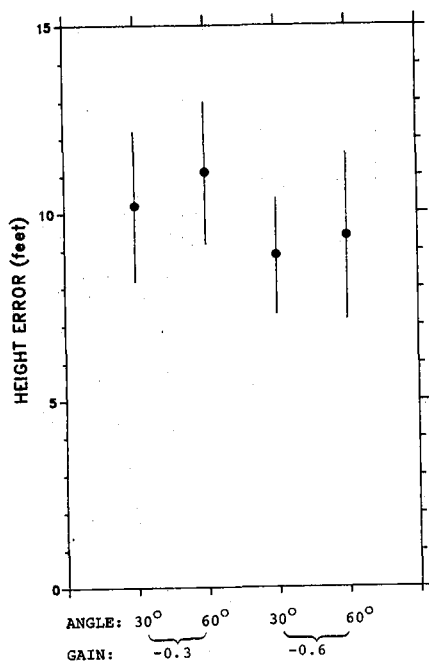
Average SD scores for height error, pitch error, "stick" (operator's control input), and stick rate are plotted in Figure 2. Solid symbols indicate group means, vertical bars indicate the standard deviation of the subject means. Figure 2a shows that superior tracking performance (lower height error scores) was achieved with the larger display gain and the smaller reference angle. Display gain had the greater effect: doubling the gain decreased tracking error by about 17% on the average, whereas reference angle influenced the score by about 7%.

Display parameters had numerically greater effects on the remaining SD scores, with gain again having the greater influence. Pitch error SD score showed the greatest fractional change, being about 45% greater for the larger display gain. Stick and stick rate also showed substantial increases for the larger display gain.

If we consider the perspective angle seen by the operator -- rather than height error -- as the major "outer-loop" variable, then the effects of display gain are consistent in that all display and control variables of interest increase with increasing display gain. The RMS central angle increased by less than a factor of 2 with a doubling of the display gain, however, as indicated by the improved tracking error. Perceptual-motor mechanisms responsible for this improvement are suggested later in the section on model results.

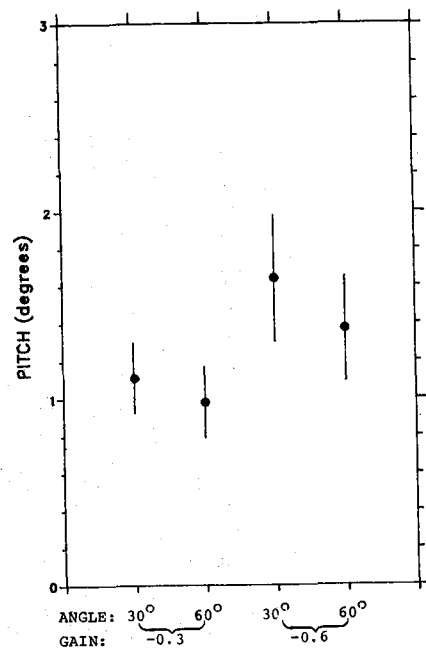
Results of subject-paired t-tests of differences in SD scores are shown in Table 2. Entries indicate alpha levels of significance; differences having alpha levels greater than 0.05 are considered "not significant" and are indicated by dashes. Two major trends are indicated by this table: (1) differences due to changes in display gain (Table 2a) were overall more significant than differences due to reference central angle (Table 2b), and (2) display-related differences in pitch and control variables were more significant than differences in height error. Because

a) Height Error



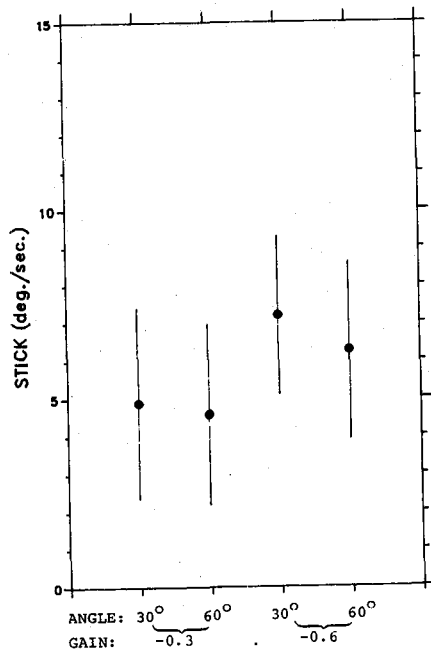
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b) Pitch Error



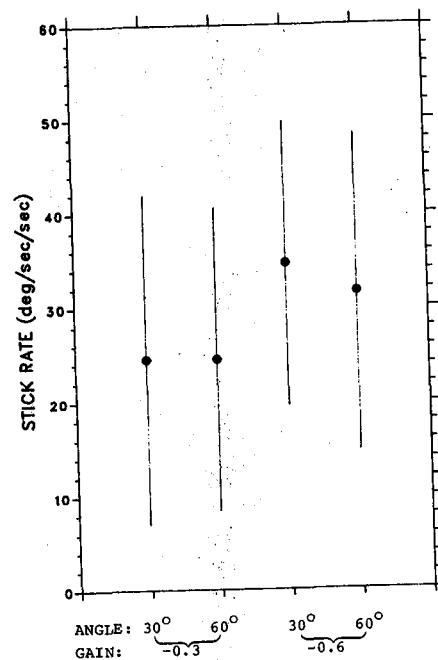
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c) Stick



0656-772

d) Stick Rate



0656-773

Figure 2. Effect of Display Conditions on SD Score
Average of 6 subjects, 4 trials/subject

Table 2. Results of Paired-Difference T-Tests on SD Scores

Condition	Height	Pitch	Control	Ctrl Rate
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a) Effects of Display Gain

30 degrees	--	.01	.02	--
60 degrees	.05	.001	.01	.02

b) Effects of Nominal Central Angle

-0.3 deg/ft	--	.05	.05	--
-0.6 deg/ft	--	.05	--	--

Entries indicate alpha significance levels. Alpha levels greater than 0.05 indicated by dashes.

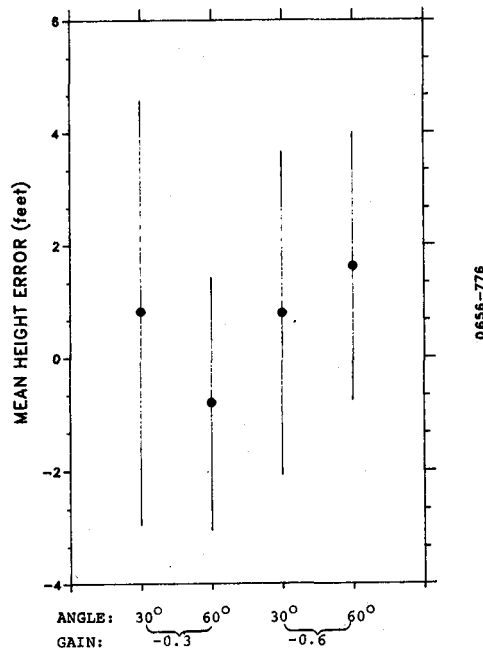


Figure 3. Effects of Display on Mean Height Error
Average of 6 subjects, 4 trials/subject

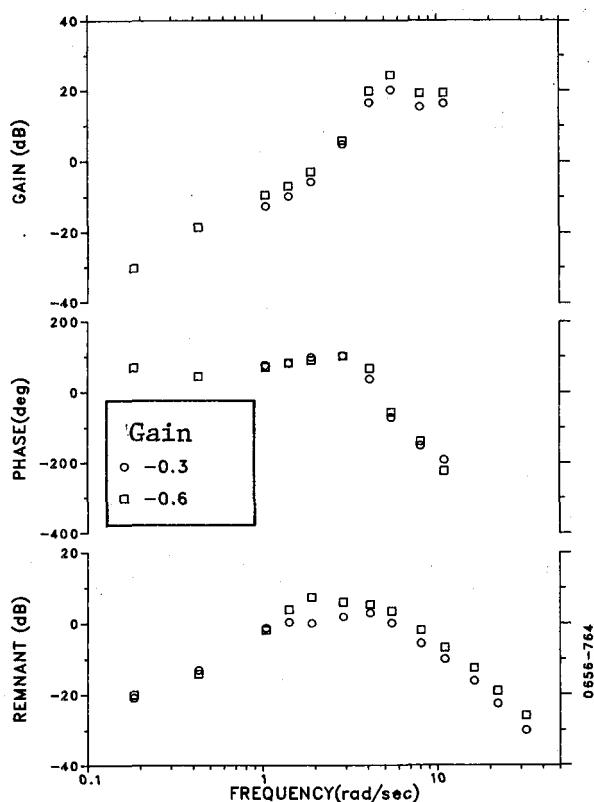
central angle effects were only weakly significant ($\alpha = 0.5$), we consider angle effects on the whole as not significant.

Mean height error, averaged over the subject population, is plotted in Figure 3. There were no significant differences in mean error across conditions and, overall, the mean error was relatively small. The absence of a substantial error bias, which is somewhat surprising given the lack of an explicit zero reference during data collection, suggests that the subjects were able to develop a relatively accurate impression of the desired roadway perspective during training.

Frequency Response

The effects of display gain on average operator frequency response are shown in Figure 4a. Results have been averaged across the two central-angle conditions; thus, each curve reflects the average of six subjects, eight replications per subject.

a) Effects of Display Gain



b) Effects of Reference Central Angle

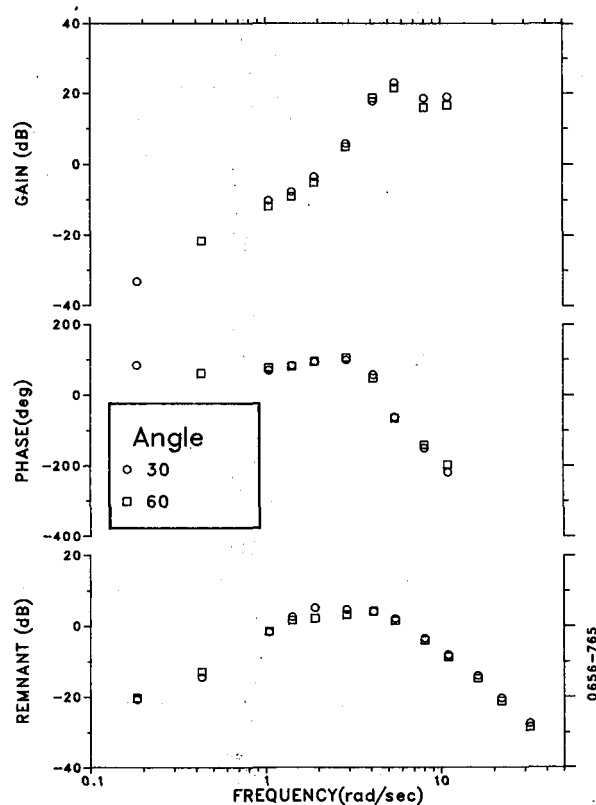


Figure 4. Operator Frequency Response
Average of 6 subjects, 8 trials/subject

Note that the term "gain" has two meanings: the sensitivity of the display in terms of degrees change of central per foot change of altitude, or the amplitude-ratio component of the

operator describing function. The particular meaning intended should be clear from the context of the discussion.

Each pair of gain and phase curves represents the effective describing function relating operator response to height error (i.e., the Fourier transform of the control response divided by the Fourier transform of the height error). Zero dB gain corresponds to one unit of control input per foot of height error; zero dB remnant indicates one unit of control power (at a given frequency) not linearly correlated with the tracking input.* These curves have not been corrected for measurement bias due to simulation delays of around 50 msec. Thus, the true operator phase shift is somewhat more positive (i.e., less phase lag) than shown here and in subsequent plots.

Each describing function shown in Figure 4 reflects the subjects' use of all available cues (e.g., height error, height error rate, pitch, and pitch rate). The frequency dependencies of these curves, therefore, should not be expected to resemble those observed in previous studies of single-variable tracking tasks.

Figure 4a shows that, on balance, the subjects tracked with a higher gain when provided with the more sensitive display, whereas differences in phase shift were negligible. This result is consistent with the trend in the error SD scores, which indicated more effective tracking with the higher display sensitivity.

The larger display gain also yielded larger stick remnant at mid and high frequencies. This result should not necessarily be interpreted to mean that the operator's response was relatively more noisy under these conditions; it may simply reflect the wider man/machine bandwidth achieved with the larger display gain. T-tests of paired differences showed that the larger gain and remnant differences were generally statistically significant.

The SD scores of Figure 2 and the frequency response measures of Figure 4a indicate that the subjects did not fully compensate for the change in display gain. Had they done so, both the scores and the frequency response measures would have been invariant with regard to display gain. Perceptual mechanisms to account for this lack of complete compensation are suggested in the discussion of model analysis.

*The F-16 control augmentation designed for this laboratory study was configured to provide the operator with a pitch-rate command. The operator's control input, therefore, has units of degrees/second.

As we would expect from the foregoing analysis of error scores, Figure 4b shows relatively small changes in frequency response due to a change in the nominal central angle. In general, angle-related differences were not statistically significant.

MODEL ANALYSIS

As mentioned earlier, the optimal control model (OCM) for the human operator is expected to provide a theoretical framework for coalescing and extending the data on visual scene cuing obtained in the AFAMRL experimental program. This model has yielded reasonable results in previous applications involving both symbolic and pictorial displays, and we believe it allows the appropriate parameterization to handle relatively simple visual scene cues such as linear perspective. Additional theoretical developments have been undertaken to develop a separate submodel for visual flow-field cuing [1,2] which, it is hoped, will eventually be integrated into the OCM.

Problem Formulation

The reader is assumed familiar with the general structure and parameterization of the OCM. For convenience, however, we review here the treatment of display-related issues.

The OCM, as currently implemented, allows a treatment of a display along the following three dimensions: (1) the state-related information provided by the display, (2) the quality of this information, and (3) dynamical aspects of the display (e.g., bandwidth limitations) that may be important. Each perceptual input provided by the display is assumed to be a linear combination of one or more of the problem state variables; if no such relationship can be found, the display is deemed irrelevant to the task. The quality of the information is represented by an observation noise, and possibly by a delay.* Dynamics associated with the physical display create new state variables which are simply lumped with the original problem state variables as part of the total "system dynamics". Because the display used in this study was free of significant bandwidth limitations, we shall discuss only the informational aspects of the display.

*The OCM, as currently configured, allows for a single pure time delay, which is often selected to reflect the time delay associated with the human operator (typically, 0.2 seconds). Display-related delays may be lumped into this operator delay (if all such delays are equal), or they may be included by means of Pade approximations.

The linear relationships between state (problem) variables and perceptual (display) variables were as follows:

$$\begin{bmatrix} \beta \\ \dot{\beta} \\ \theta \\ q \end{bmatrix} = \begin{bmatrix} K & 0 & 0 & 0 \\ 0 & K & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} h \\ \dot{h} \\ \theta \\ q \end{bmatrix} \quad (3)$$

where the vector on the left includes visual variables in degrees, and the vector on the right includes state variables in problem units. The parameters of this expression were defined as follows:

β = perspective central angle, degrees
 $\dot{\beta}$ = central angle rate, deg/sec
 θ = pitch, degrees
 q = pitch rate, deg/sec

The display gain K was computed as

$$K = - \frac{57.3 W}{H^2 + \frac{W^2}{4}} = 57.3 \cdot \partial\beta/\partial H \quad (4)$$

where H and W are roadway height and width in feet.

This formulation reflects a small-signal linear analysis about the nominal (reference) condition. The display and state vectors shown above, therefore, include only the variational components and do not include reference values or mean errors. On the other hand, all coefficients of the transformation matrix (including the reference height H) were fixed at reference values, and variations in central angle were therefore proportional to variations in height. This approximation was not made in the experimental study, where the full trigonometric relation between perspective angle and roadway parameters was implemented continuously during each experimental trial.

In keeping with previous analysis, each perceptual variable was assumed to be corrupted by an additive white noise process with autocovariance determined by:

$$V_Y = \frac{\pi P}{f} (\sigma_Y^2 + \sigma_{Y0}^2) \quad (5)$$

where V_Y is the autocovariance, P a noise/signal ratio to account for the scaling aspects of this "observation noise" process, "f"

the fraction of attention allocated to the perceptual variable, $\frac{2}{y}$ the variance of the signal as presented on the display, and $\frac{2}{y_0}$ a "residual noise" variance to provide a statistical representation of perceptual resolution limitations (i.e., perceptual "threshold"). The reader is referred to Baron and Levison [6] for further details on the display submodel, and to Levison [7] for a discussion of the treatment of attention-sharing.

Note that one of the experimental variables -- display gain -- was reflected directly in the linear relationship between state and perceptual variables (Equation 3). The other experimental variable -- nominal central angle -- influenced the model analysis in the selection of residual noise levels associated with perception of central angle and angle rate. That is, the fidelity with which the operator could extract height-related information from the display was assumed to be potentially dependent on the nominal central angle.

Pre-Experiment Model Analysis

Pre-experiment model analysis was performed to aid in the selection of values for the major experimental variables (central angle and display gain). Using the results of a recent modeling effort as a basis [8], the following values were assigned to independent "pilot-related" model parameters:

Observation noise/signal ratio = -20 dB

Motor noise/signal ratio = -60 dB

Time delay = 0.2 seconds

Motor time constant = 0.13 seconds*

Additional parameters related to the perceptual process were adjusted to reflect various assumptions concerning attention-sharing and perceptual resolution limitations, as described below.

A baseline observation noise/signal ratio of -20 dB was

*Readers familiar with applications of the OCM will recall that motor time constants of around 0.1 seconds have typically been specified when using the model as a predictive tool. We felt that this larger value, which was based on a recent study involving roll-axis tracking in the presence of important simulation-related lags, would be more appropriate than the lower value based on idealized tracking dynamics (e.g., no simulation lags).

associated with nominal "full attention" to the tracking task. Noise ratios associated with particular display quantities were scaled inversely with attention (see Equation 3) to reflect attention-sharing penalties between attitude and path variables. Preliminary model analysis revealed that a simulated attention split of 50% to path and attitude variables yielded predicted performance scores very close to those predicted for optimal allocation of attention. Therefore, the bulk of the model analysis was performed for equal attentional allocation (i.e., a noise/signal ratio of -17 dB for all perceptual inputs).

Pre-experiment predictions of the (zero-mean) RMS height error are shown in Figure 5 for a variety of assumptions concerning perceptual resolution limitations. Condition A reflects an idealized perceptual environment without perceptual resolution limitations and serves as a baseline for exploring the effects of such limitations. Conditions B through D reflect increasingly pessimistic assumptions concerning effective perceptual thresholds associated with the pitch and roadway (angle) display variables. (See Levison et al for additional details [4]).

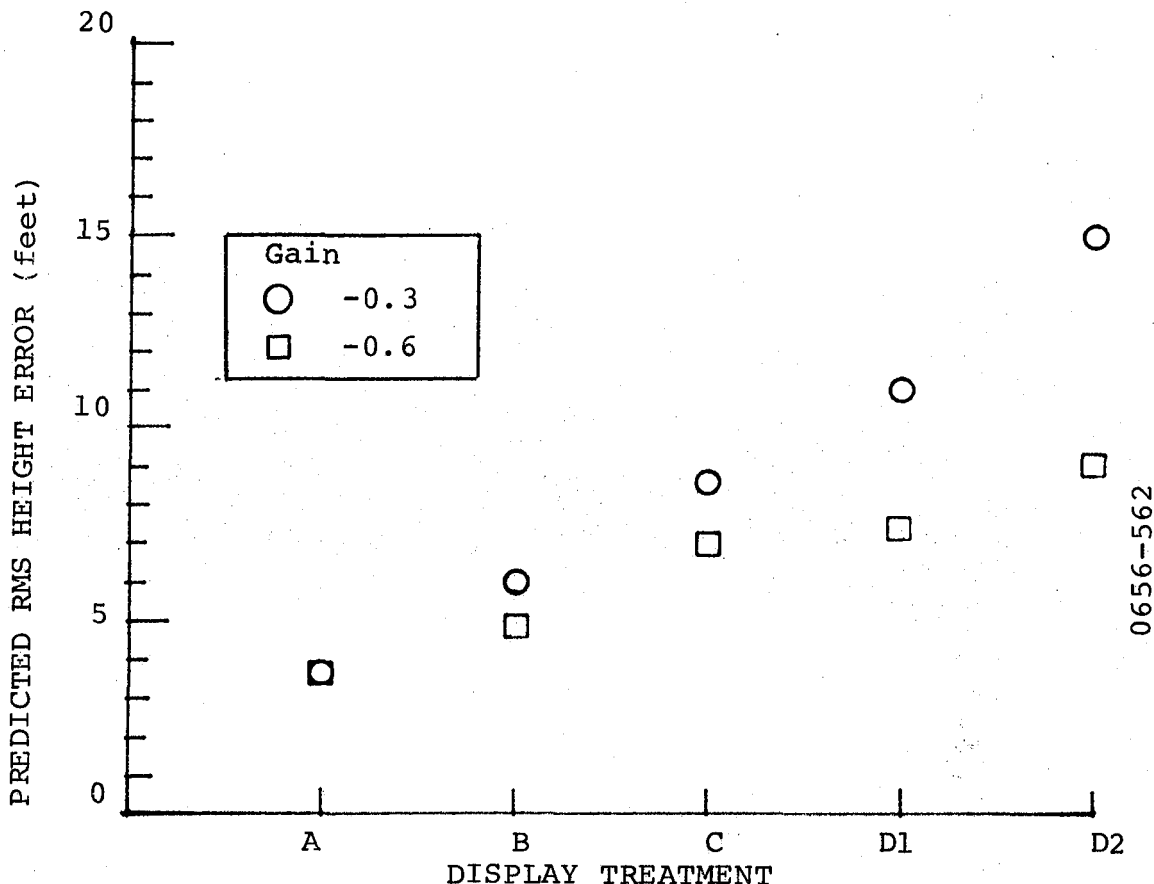


Figure 5. Effects of Display-Related Limitations on Predicted RMS Height Error

Conditions B and C assume constant (but different) thresholds associated with perception of the perspective central angle and angle rate. For these cases, the OCM predicts performance effects due to display gain, but not due to differences in nominal central angle. (As the display gain increases, the RMS variation in central angle increases with respect to the assumed perceptual "threshold", allowing the subject to obtain better estimates of his altitude and therefore track more effectively.)

To account for performance effects related to central angle, condition D assumes that the residual noise variance (Equation 5) associated with perception of central angle varies with the mean-squared value of the central angle. In this case, a larger residual noise is associated with the 60 degree central angle (condition D2) than with the 30 degree angle (D1), and, as Figure 5 shows, performance effects of both central angle and display gain are predicted.

As noted above, the primary objective of this pre-experiment analysis was to aid in the experiment design; specifically, to allow us to select parameters having a reasonable likelihood of showing a performance effect. On the basis of Figure 5 we predicted that, for the display gains and angle selected, there would very likely be a measurable performance effect due to display gain, and possibly one due to central angle. A comparison of the predictions of Figure 5 with the experimental height error scores of Figure 2 shows that the data fell within the range of pre-experiment predictions and corresponded most closely to the set of (relatively pessimistic) assumptions reflected in condition D1.

Post-Experiment Model Analysis

The condition yielding best performance (30 degree reference angle, -0.6 deg/foot display sensitivity) was selected as the baseline condition for initial model analysis. Group-mean performance scores and frequency response measures were matched via the OCM with all independent parameters allowed to vary. The parameter set consisted of four observation noise quantities: one each for the presumed observations of height error, height error rate, pitch "error", and pitch rate; a motor noise; a time delay; and a motor time constant.

The resulting model response (smooth curve) is compared with experimental results (discrete symbols) in Figure 6. At all but the lowest and highest measurement frequencies, model and data exhibited very close correspondence. The composite scalar matching error (which includes SD performance scores as well as frequency response) indicated that experimental measures were matched to within about 1 standard deviation on the average.

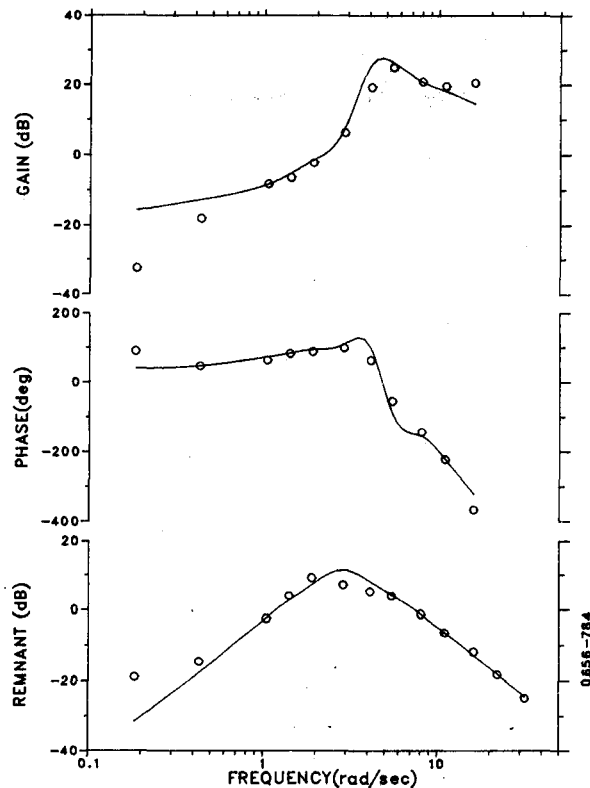


Figure 6. Model Match to Average Operator Frequency Response.
 30 degree reference angle, -0.6 deg/foot.
 Average of 6 subjects, 4 trials/subject.

With seven model parameters adjusted in the search procedure, there existed substantial potential for "tradeoff" among parameters in obtaining a near-optimal match to the data; thus, the resulting parameter set cannot be expected to provide a reliable estimate of intrinsic human information processing limitations.* Rather, the goal of this initial post-experiment model analysis was to provide a baseline against which to compare model analysis employing reasonable constraints among the independent parameters.

Further model analysis was pursued with the goal of developing a tool having useful predictive capabilities. The approach adopted was to fix as many operator-related parameters as possible at values based on previous results, and to "search"

*Some of the parameter values yielded by this unconstrained search were outside the range of expectations. For example, the observation noise associated with perception of central angle was unusually low, whereas unusually large values were found for the time delay and motor time constant parameters.

the parameter space as little as possible. Accordingly, the observation noise/signal ratio was fixed at -20 dB; baseline equal attention to height- and pitch-related display variables was assumed; motor noise was set to -50 dB; the time delay parameter was set to 0.25 seconds (0.2 for the human operator plus 0.05 for simulation delays); and the motor time constant was set to 0.133 to provide an apparent best match for this particular parameter.

RMS residual noise levels* associated with pitch and pitch rate were fixed respectively at 3.0 degrees and 0.84 deg/sec, respectively, and a residual noise of 3.0 deg/sec was specified for perception of central angle rate. (These values correspond to those selected for condition D during pre-experiment analysis.) The remaining free parameter -- residual noise for perception of central angle -- was then adjusted to a value of 30 degrees (RMS) to provide the best match to data from the baseline experimental condition (30 degrees, -0.6 deg/foot). The resulting scalar matching error was within 20% of that obtained previously with no constraints on the seven independent parameters.

Having matched the baseline condition, our next modeling objective was to determine whether or not a consistent treatment of visual scene cues (along with other operator limitations) would allow the OCM to mimic the experimental trends. Accordingly, the model was tested against a low-display-gain condition (30 degree central angle, -0.3 deg/foot display gain) with the parameters fixed at values determined from matching the baseline condition.

There was some ambiguity, however, as to what constituted a "fixed" parameter set. Recall* that the motor time constant parameter derives from a performance penalty associated with rate-of-change of control (i.e., a "cost" on control rate variance). For a given set of system dynamics, there is a unique relationship between these two parameters (provided other

*Other applications of the OCM have tended to use an alternative treatment of effective perceptual threshold in which the observation noise is a more severe function of "threshold" than indicated by Equation 5 above. For equivalent influence on estimation and control performance, the "residual noise" of the current treatment is about 3 times as great as the "threshold" parameter of the alternative model described in Baron and Levison [6].

*Readers unfamiliar with the mathematical structure of the OCM are directed to References [9,10].

components of the quadratic performance index are invariant).^{*} When the system matrices are changed, however, this relationship changes. Thus, we had the choice of fixing either the motor time constant (which would require a corresponding change in the control-rate cost coefficient), or of fixing the cost coefficient and accepting a different motor time constant. The first option would imply a consistent human operator bandwidth limitation; the second, a consistent subjective penalty on control activity.

Because the motor time constant has tended to be less variable across conditions than the control-rate penalty [8], this parameter was held fixed in the first test of the low-display-gain data. While an increased height error score was predicted, the model did not mimic the trends of the pitch and control-related scores, nor did it replicate the experimental trends in operator frequency response.

Considerably better results were achieved by maintaining a constant performance penalty. Table 3 shows that experimental trends were replicated; specifically, a reduction in display gain resulted in a larger predicted height tracking error and in lower pitch and control-related scores. While not demonstrating the type of precision match usually obtained in a laboratory setting, the predicted frequency response shown in Figure 7 also mimics certain important trends; specifically, the generally lower operator gain and lower high-frequency bandwidth observed for tracking with the low display gain. The overall scalar matching error for the low-gain experimental condition was on the order of 1 standard deviation, which compares favorably with the initial model-matching exercise in which all parameters were adjusted for optimum match.

DISCUSSION

Experimental results and model analysis support the following hypotheses concerning the effects of display gain on operator performance:

1. As the display gain increases, the variations in perspective angle are increased relative to the operator's limitations in resolving angle differences, and the resulting signal/noise enhancement provides better height-related information with resulting improvement in height tracking performance.
2. Because the operator maintains with a fixed subjective

^{*}The control-rate weighting term was actually identified by the gradient search procedure, then converted to a motor time constant for presentation.

Table 3. Comparison of Experimental and Model SD Scores

Variable	High Display Gain			Low Display Gain		
	Model Mean	Experimental Mean	Std Dev	Model Mean	Experimental Mean	Std Dev
Height	7.83	8.87	1.57	11.0	10.2	2.03
Pitch	1.41	1.64	0.34	1.23	1.11	0.19
Stick	8.27	7.20	2.10	4.46	4.88	2.53
Stick Rate	40.6	34.7	15.1	22.6	24.5	17.5

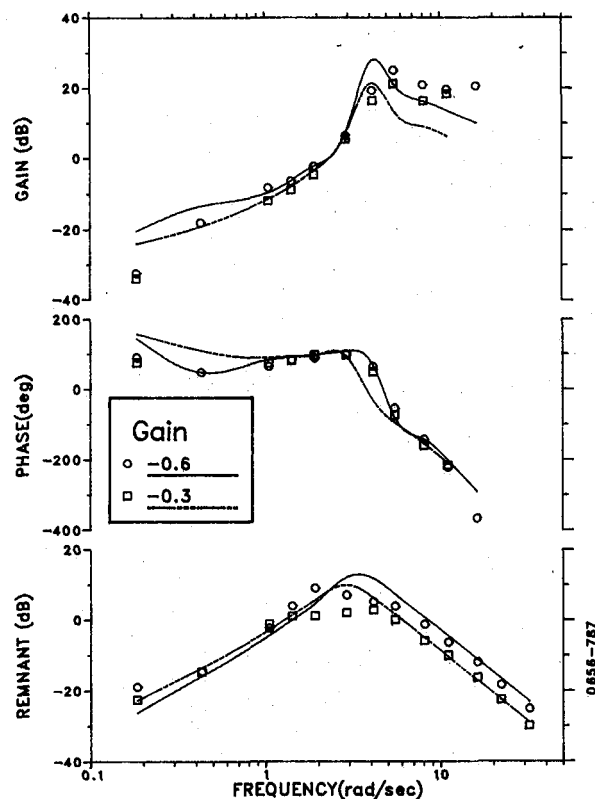


Figure 7. Comparison of Experimental and Model Frequency Response. Experimental results shown by discrete points, model results indicated by smooth curves.

penalty on mean-squared control-rate, relative to mean-squared display error, the larger display excursions accompanying the larger display gain motivate the operator to respond more aggressively, thereby increasing closed-loop system bandwidth and reducing height error.

The first-cited of these display-gain effects was anticipated prior to initiation of the experimental study and was revealed in the pre-experiment model analysis. The second hypothesis is based on post-experiment analysis and was not specifically anticipated. Other interpretations of the experimental results are discussed shortly.

Effects of central angle were not so obvious prior to the experiment. One could argue for certain angle configurations (say, very small or close to 180 degrees) for which small variations could be readily detected by the human observer, but it was not clear how performance should differ between a 30-degree and a 60-degree central angle. The hypothesis that a perceptual noise variable would scale with mean-squared central angle proved overly pessimistic. The experiment revealed a small and not statistically significant effect of central angle on height error. Additional experimentation would be necessary to determine whether this result extends to other values for central angle and other tracking tasks.

The residual noise value of 30 degrees associated with perception of central angle was much larger than expected. Based on previous experience with the OCM, we would relate this noise level to a "threshold" of around 10 degrees as might be measured in a standard psychophysical experiment. Previous studies [11], however, have shown that operators can discriminate angle differences much more precisely. It is worth noting that the composite scalar model-matching error was relatively insensitive to this residual noise parameter (provided the noise was relatively large), and that adjusting this noise influenced mainly the match to height tracking error (which, of course, is the major variable of concern when performing low-level flight).

Because height error, for this task, was a relatively low-bandwidth "outer-loop" variable, we suspect that the residual noise parameter may have accounted for more than simply perceptual resolution limitations. Two possibilities are suggested. First, despite the extensive training given the test subjects (an average of 43 trials prior to data collection), it is possible that there was some tendency for the subjects to average their response strategies across tasks. Such a tendency would cause the subjects to track with a higher response gain when presented with the higher display gain. One way to model this behavior would be to modify the "internal model" element of the OCM to contain an average representation of display gain.

Another internal-model deficiency to consider is the potential interaction between the pilot's internal model and the difficulties posed by the task environment (perceptual limitations, system lags and delays). Previous analysis [8] provides some qualitative support for the notion that significant system lags and delays, for example, impede the operator's ability to construct an accurate internal model. It is possible that there may have been a double effect associated with the central angle display: namely, the relatively large perceptual resolution limitations associated with the angle display may have interfered with development of an adequate model for low-frequency system response; an inadequate model, in turn, would cause still larger height errors.

We noted above two methods of treating the control-rate cost coefficient: either hold this parameter fixed across tasks, or let it vary in a way that maintains an invariant motor time constant. A recent study of control-stick parameters suggests a more general treatment; namely, that this coefficient be adjusted to reflect both an operator response bandwidth limitation as well as a true subjective penalty on control response [12].

Although certain modeling issues remain to be resolved, we feel that the OCM provides a suitable model framework for integrating the effects of various cuing environments and various task environments to yield useful predictions of the operator's estimation and control strategies. To include the effects of a perceptual cue that has not been previously explored, some "calibration" is required to quantify appropriate model parameters to reflect the information content, information quality, and dynamical characteristics of the display providing the cue.

There are a number of ways to perform such a calibration. The procedure followed in the pre-experiment design phase of this study was to look to the tracking and psychophysical literature for guidelines concerning perceptual limitations. In our case, this process yielded an experiment design for which operator performance was significantly influenced by at least one of the experimental variables.

Another calibration method is to develop a separate submodel for the perceptual cue(s) of interest, and use this model to determine relevant OCM parameters. This approach was followed in the design of an experiment to explore flow-field cues [4]. A third procedure is to perform an experiment in a tracking or psychophysical setting to explore directly the operator's ability to utilize the cues of interest.

One of the lessons learned from this study is that a complex task simulation is not well-suited to display calibration because of the complex cuing environment. Because the operator will typically utilize all relevant cues available, his response to a

particular cue of interest is confounded by his response to the remaining cues. Simulations of this sort are most useful for testing hypotheses in operationally-relevant settings, but not in performing detailed diagnosis.

Display calibration is best executed in simple experiments in which the cuing environment is tightly constrained; ideally, only the cue of direct interest should be available. Constructing an experiment of this sort is not always a trivial task, particularly when attempting to isolate one of many cues that may be present in a rich visual scene; nor is it clear how to extrapolate measures obtained in a passive psychophysical setting to a manual control task in which the displayed variables are influenced by operator actions. Further methodological development remains to be done in this area.

SUMMARY AND CONCLUSIONS

Six test subjects performed a fixed-base tracking task with a visual display consisting of a simulated horizon and a perspective view of a straight, infinitely-long roadway of constant width. Experimental parameters were (1) the central angle formed by the roadway perspective (30 or 60 degrees) and (2) the display gain (-0.3 or -0.6 degrees change in central angle per foot change in altitude). The subject controlled only the pitch/height axis. The subject's primary task was to maintain a fixed height above ground in the presence of simulated random gusts.

Experimental results showed the following trends:

- o Display gain had a greater influence on the average height error standard deviation (SD) score than did central angle. Doubling the display gain resulted in an average reduction in tracking score of about 17%, whereas doubling the central angle increased the height error score by only 7%.
- o Display parameters had greater influence on pitch and control-related scores, with a doubling of the display gain resulting in a 45% increase in the pitch SD score.
- o The larger display gain resulted in a larger operator response gain (i.e., amplitude ratio), little change in phase shift, and greater high-frequency remnant. The increased remnant is attributed to increased man-machine system bandwidth, not to increased "noisiness" in the operator's information processing.
- o Gain-related effects tended to be statistically more significant than angle-related effects.

- o The relatively small mean height errors suggests that the subjects were able to construct good internal models of the reference central angle.

A fixed set of model parameters was found to replicate the trends of the display-gain variations. Model analysis supports the notion that two factors accounted for the improvement in height regulation with increasing display gain: (1) excursions of the perspective central angle are increased relative to the effective perceptual threshold, and (2) the larger apparent tracking error indicated by the display motivates the operator to track more vigorously and thereby increase closed-loop system bandwidth.

In order to match experimental results with an otherwise reasonable set of independent model parameters, a relatively large value was required for the "residual noise" model parameter associated with perception of central angle deviations. We therefore speculate that this parameter reflected other, non-perceptual, limitations on operator performance, including (1) a tendency to adopt an average response strategy for the four experimental conditions, and (2) some imperfections in the operator's ability to construct an accurate internal model of system response at low frequencies.

On the basis of this study we conclude that the OCM, as currently configured, provides a suitable framework for modeling the effects of visual scene cues of the type explored here, and that it can be used very effectively in the design of simulation experiments. We also conclude that simulations of complex realistic flight tasks should not be employed for quantifying the operator's use of specific perceptual cues, but rather for testing hypotheses in task-relevant settings. Instead, we recommend that studies of cue utilization employ relatively simple tasks in which the cuing environment is constrained as much as possible to include only the cues of specific interest.

To enhance the accuracy of the model as a tool for predicting visual cuing effects, we suggest the following two areas for further attention:

Improved methodology for "calibrating" the operator's utilization of various perceptual cues, and for extrapolating measures obtained in a standard psychophysical setting to model parameters relevant to estimation and control.

Refine the OCM to account for the possible interaction between certain task parameters and the operator's internal model of the task environment.

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